An Effective Understanding of Dark Matter Constraints

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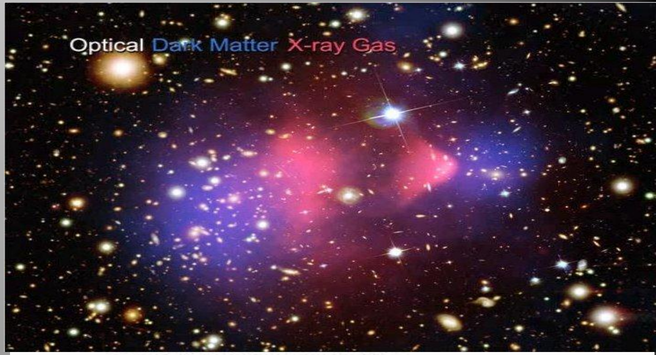
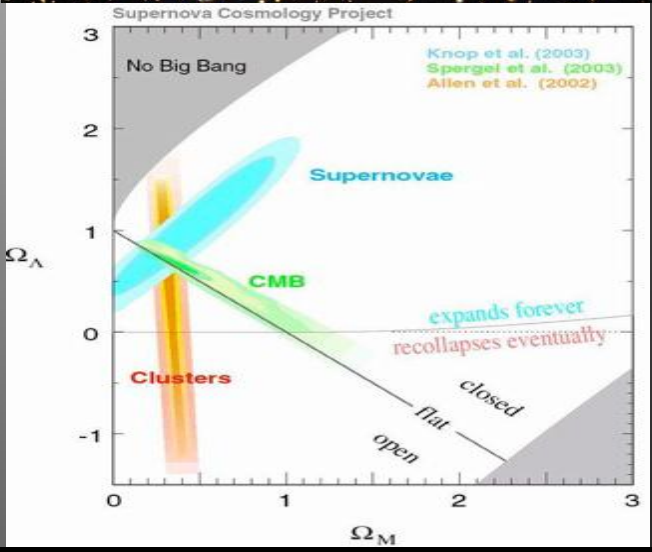
Related work: Bai, Fox, Harnik [1005.3797]

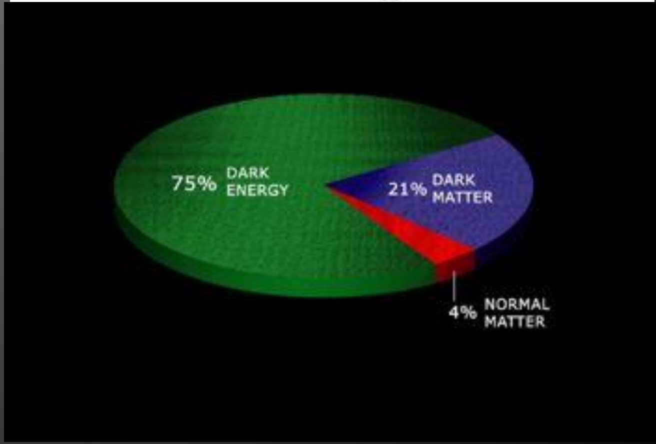
Goodman, Ibe, Rajaraman, WS, Tait, and Yu
[1005.1286], PLB
[1008.1783], PRD
[1009.0008], NPB

Dark Matter

- The evidence for dark matter is myriad and well-known.
- This is one of the only truly experimental signs that we must have physics beyond the Standard Model.
- Cosmological observations tell us how much dark matter is needed to match observations.
- From the particle physics perspective, we're left asking what dark matter is and how it fits into a microscopic understanding of nature.







WIMP Dark Matter

- One of the most attractive proposals to explain dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally lead to the correct amount of dark matter in the universe.
  - WIMPs are automatic ingredients of many models of physics beyond the Standard Model, such as supersymmetric models.
- Instead of the usual approach of assuming a specific particle model for dark matter, I’ll do what I can to consider all of them using effective theories.

What we know about WIMPs

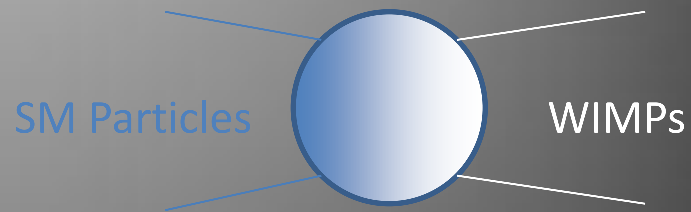
- Dark matter is, first of all, a new particle
  - It is neutral, massive, and (at least cosmologically) stable.
- We still have a lot to learn (or guess at)
  - Spin
  - Electroweak charge
  - Self-conjugacy
- We want an understanding of all the possibilities if we hope to say anything true about dark matter in general.

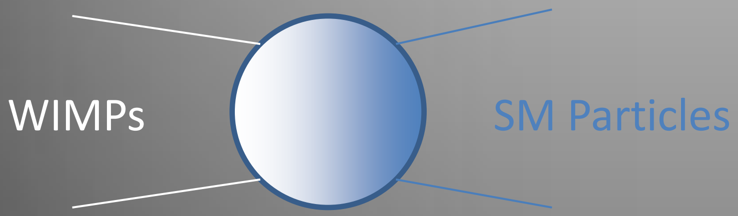
WIMP Interactions

- When it comes to searching for dark matter, WIMPs are also quite exciting, since they have "strong" interactions with the Standard Model.
  - Strong means similar to electroweak strength here – much stronger than gravity.
  - The interesting point is that we can actually search for these particles outside gravitational observations.
  - A non-gravitational observation would teach us a lot.

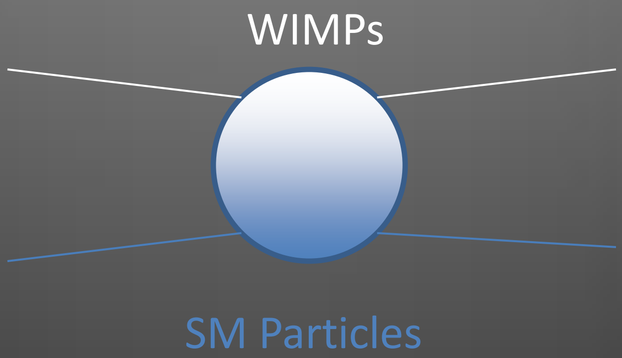
Many Places to Look

Collider Searches



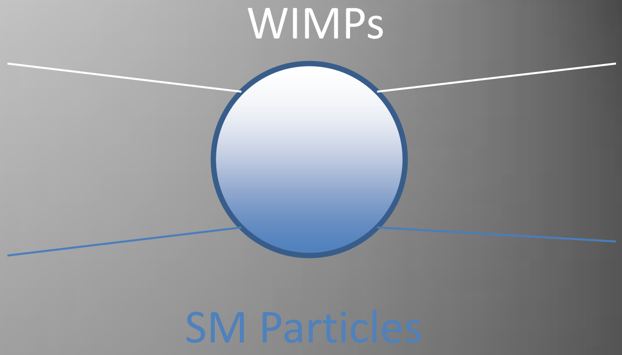


Indirect Detection

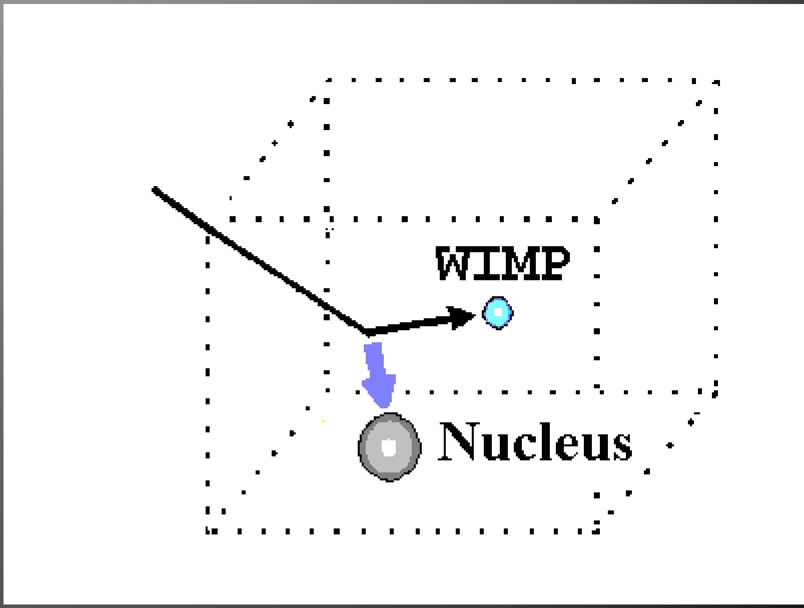


Direct Detection

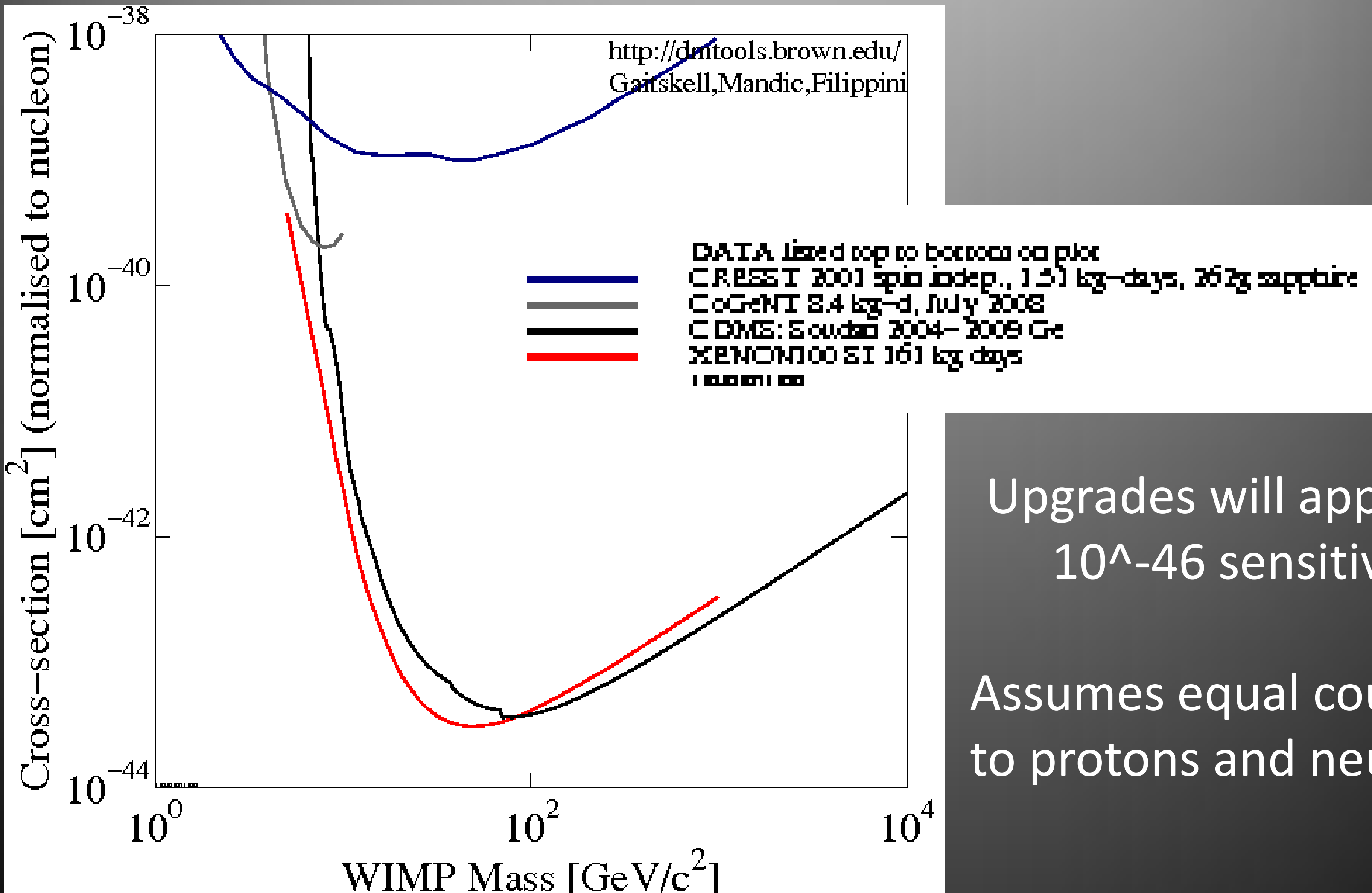
Direct Detection



- The basic idea of direct detection is to catch a low energy recoil of a nucleus from an interaction with a WIMP.
- Shielding is key to screen out Standard Model backgrounds.
- The source of the recoil can be determined by additional characteristics of the interaction (scintillation, timing, ionization).
- The rate depends sensitively on the local distribution of dark matter and its velocities.



~~Today's~~ Yesterday's Status



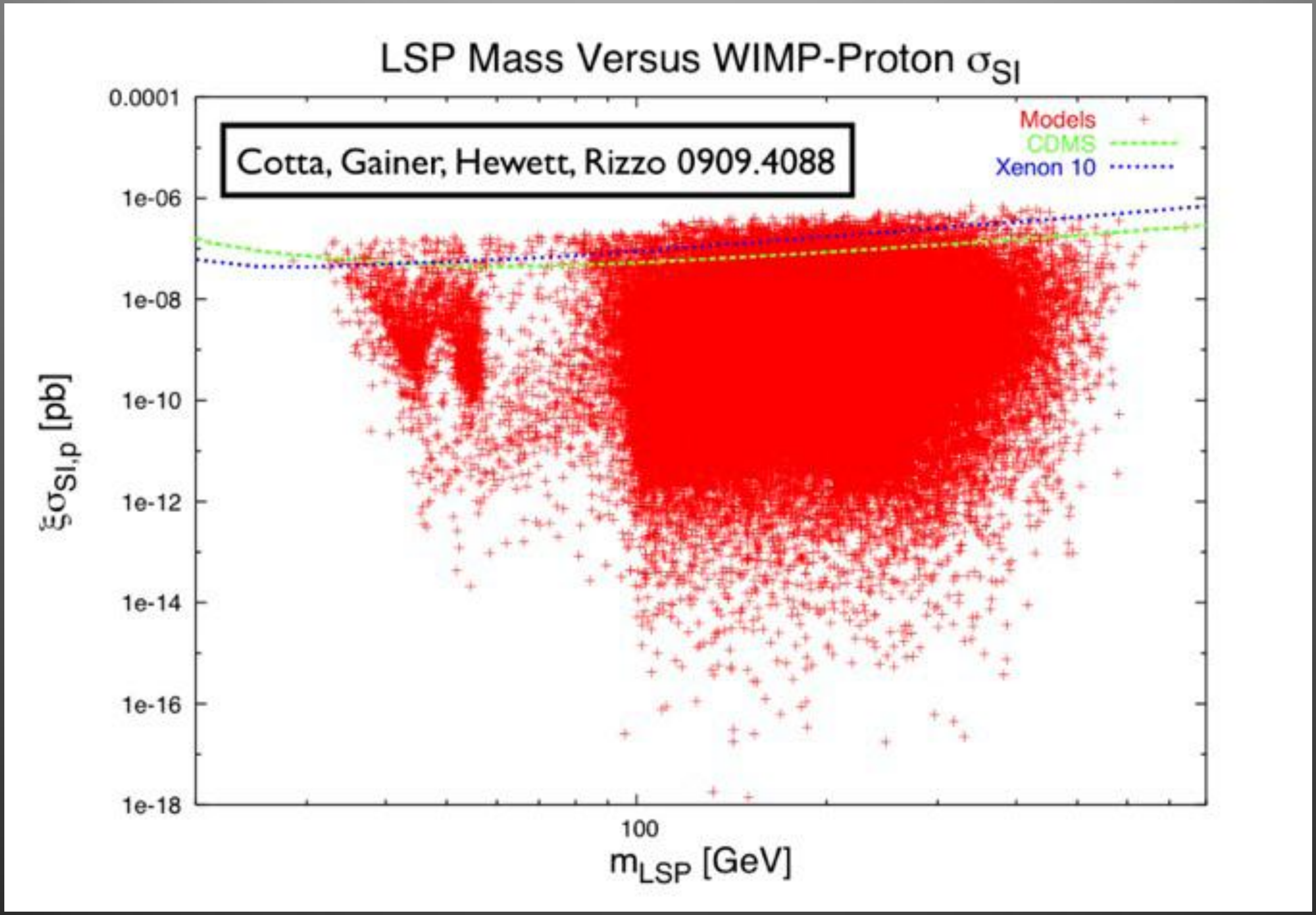
Upgrades will approach 10^-46 sensitivity

Assumes equal couplings to protons and neutrons.

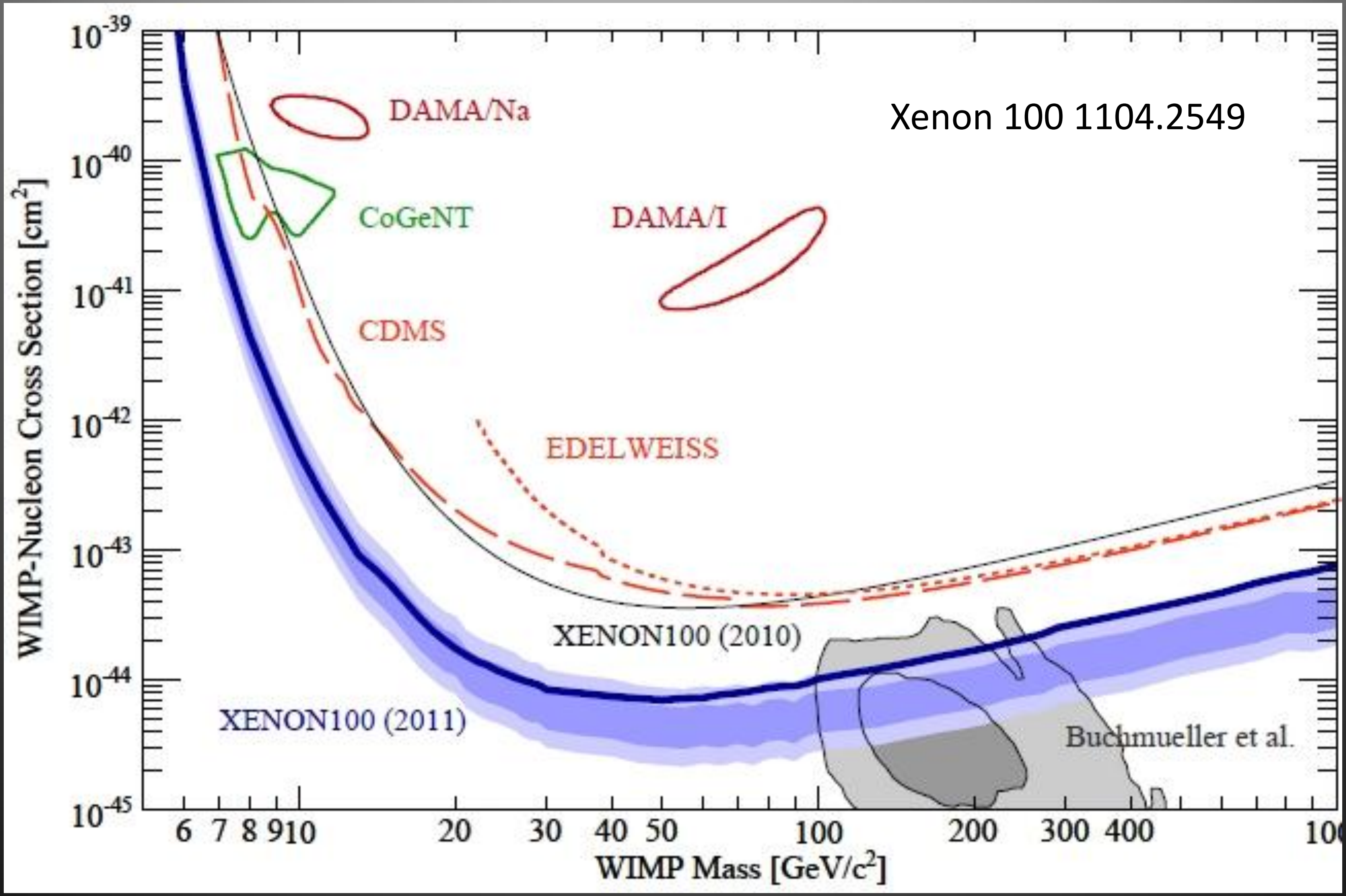
The Question of the day:

How can we relate the many different strategies for finding dark matter to one another?

Colliders Have Something to Say About Direct Detction

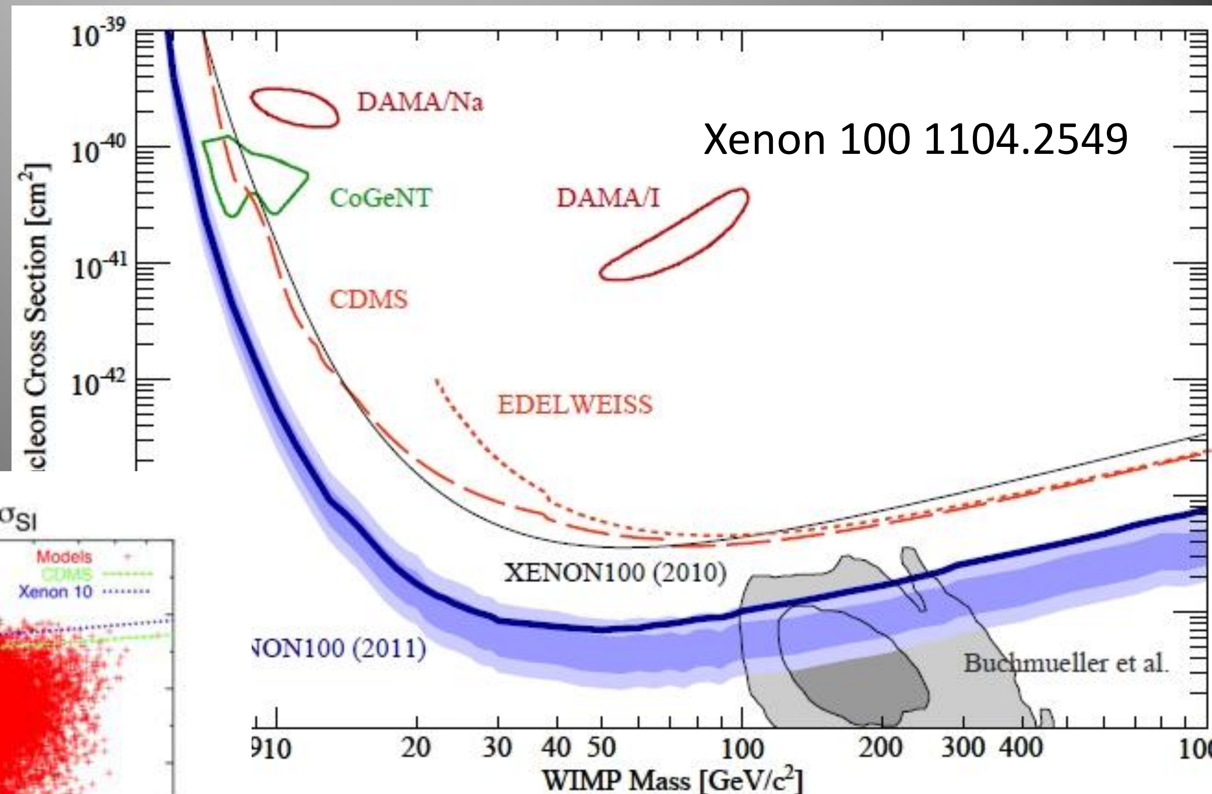


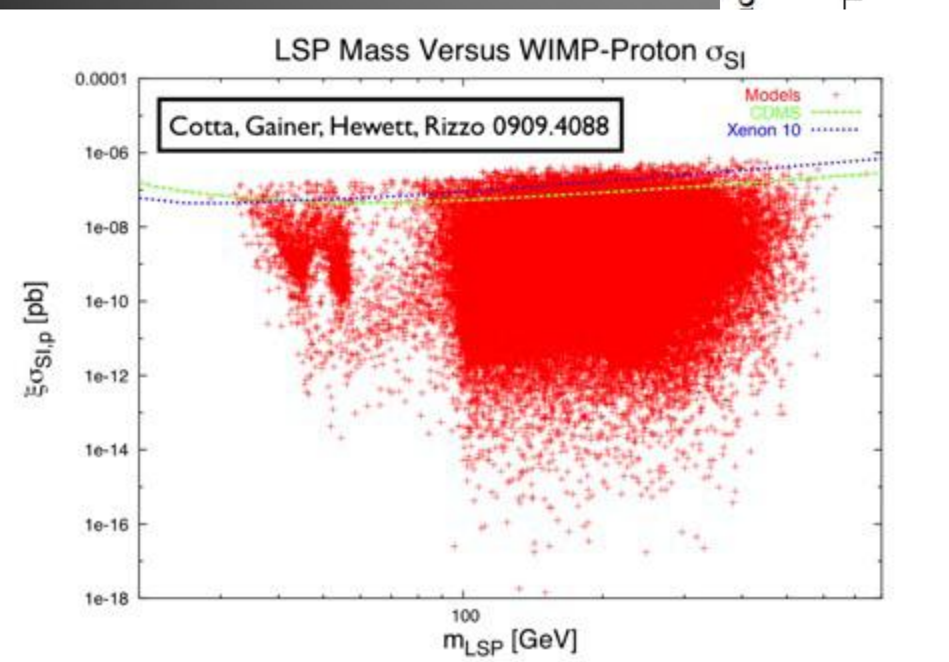
But what do they say?



Different Answers?

Same model, the MSSM





But very different questions.

One takes the CMSSM seriously, constructing the most likely parameter space.

Second just asks for generic points obeying constraints…

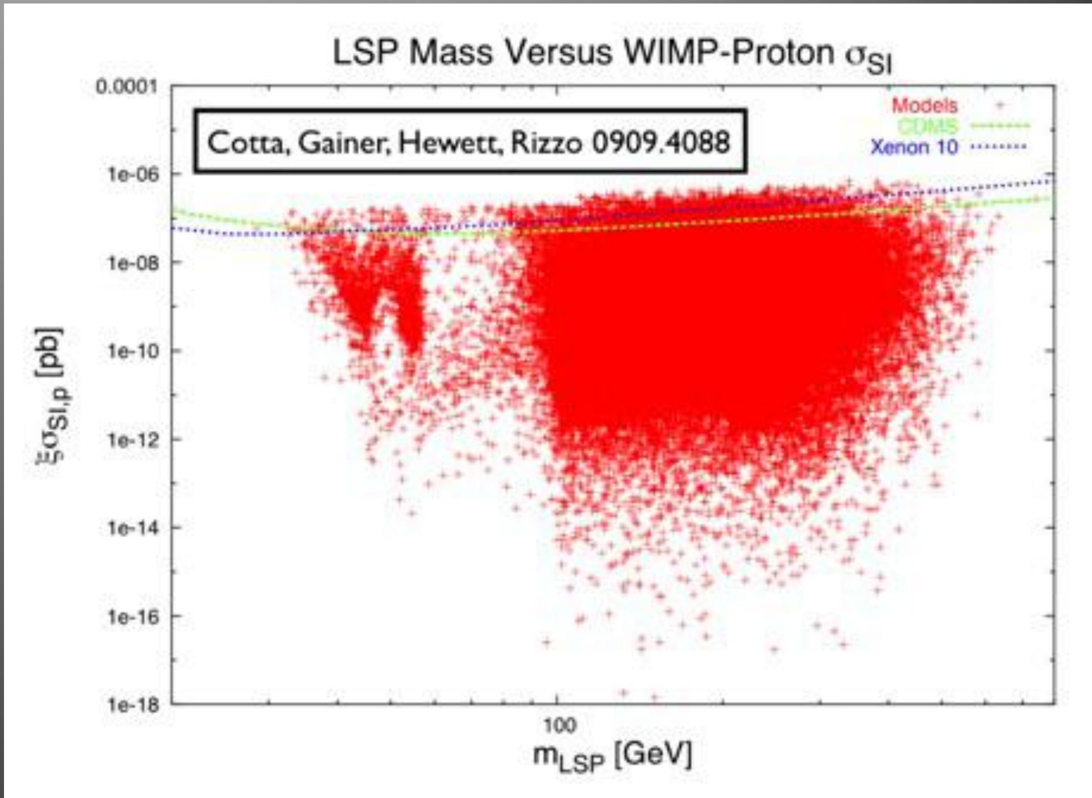
Open Questions

This plot still leaves many questions unanswered.

How do these points move around when I make small parameter changes?

What collider search will find each of these points?

How good a representation of other models (non-SUSY or even NMSSM) is this set of points?



Effective Theory

- What I'd like to tell you about today are effective quantum field theory (EFT) descriptions of dark matter.
- The goal is to capture the physics of WIMP models in a way that is fairly insensitive to the details of the models themselves.
- As effective theories, they can only describe physics correctly within some energy range, and they have very specific assumptions built in to them. Whether they work or not will depend on what kind of WIMP nature has given us for study.
- They provide a dictionary for studying the interactions of WIMPs with Standard Model fields. Using this dictionary we can translate results from one type of experiment onto the signal space of another.

The First Step:

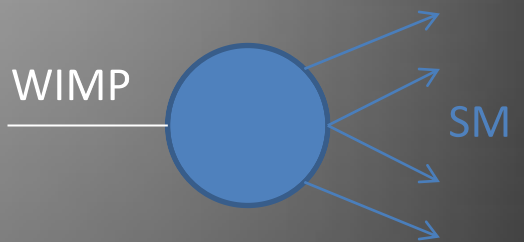
Choose your assumptions

#1: Choose a WIMP Spin

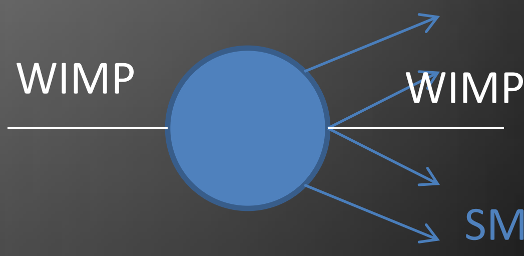
- I'll only consider WIMPs which are spin 0 or ½.
  - This covers standard fermionic and scalar WIMPs (Majorana or Dirac fermions, complex or real scalars).
  - Vector WIMPs involve a higgsed gauge symmetry, needing more baggage than lower spin objects as a result.
    - We still lose out on the LKP of UED.
  - Higher spin WIMPs? Possibly a composite state of new fields.
- All these other cases are worth looking at as well!

#2: Take the WIMP as Stable

- I will assume that the WIMP is completely stable. We know we need a lifetime comparable to the age of the universe or longer.
- This means that there is always an even number of WIMPs in any interaction.
- This is equivalent to a new 'dark parity' being exact. For a complex WIMP it could be an entire U(1) 'dark charge' symmetry.



The WIMP decays.



WIMP-Number is conserved.

#3: The WIMP is it!

- It's very important to decide what degrees of freedom are included in your EFT.
- All the states relevant for the process we're interested in need to be included.
- I will assume we have no new fields other than the WIMP.
  - I'll even assume the SM higgs is heavy.
- It is easy to relax these assumptions.
- They work for SUSY and UED type theories, but they prevent us from saying anything about new light states such as the 'dark photon'.

#4: The WIMP is a SM Singlet

- We need to assign gauge representations to the WIMP as well, and I'll choose a complete singlet.
  - Similar to the Bino in SUSY, $B^{(1)}$ in UED.
- As a result, the WIMP doesn't have charged SU(2) relatives with nearby masses or electroweak strength couplings through the W and Z bosons.
  - The WIMP could still have couplings to Ws and Zs induced by heavier states we're integrating out of our EFT.
- I also don't consider the possibility of a coupling through a light 'Higgs portal' – a heavy Higgs can be fit into our theory, however.

Eg: Kanemura, Matsumoto, Nabeshima, Okada 1005.5651

#5: Extra-Minimal Flavor Violation

- Finally, I'll choose a flavor structure that prevents the WIMP from mediating flavor or CP violation
  - Scalar combinations of SM fermions are proportional to the fermion masses.
  - Vector combinations have universal couplings.
  - I could allow different couplings to up and down type quarks without losing MFV.
  - For tensor operators I won't follow this prescription, just to interface with the direct detection literature.

$$\sum_q m_q \bar{q} q$$

$$\sum_q m_q \bar{q} \gamma_5 q$$

$$\sum_q \bar{q} \gamma^\mu q$$

$$\sum_q \bar{q} \gamma^\mu \gamma_5 q$$

$$\sum_q \bar{q} \sigma^{\mu\nu} q$$

Full Theory to EFT

- Here's the basic picture for a SUSY-like Majorana WIMP getting EFT couplings to quarks or gluons.
  - Quarks:

  - Gluons:

  - Each of these needs new states heavier than the WIMP.

Example EFT: Majorana WIMP

- For example, we can write down the interesting operators for a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and good gauge symmetries of the SM which couple WIMPs to quarks and gluons.
- Gluon operators are normalized by αs, consistent with their being induced by loops.
- Each operator has a distinct coefficient M* which parametrizes it’s strength.

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

$$\sum_q G_\chi[\bar{\chi}\Gamma^\chi\chi][\bar{q}\Gamma^q q]$$

Dirac WIMPs

- We can repeat the exercise for other WIMP properties
- For a Dirac WIMP, we have a few more allowed Lorentz structures
  - Vector and Tensor operators are allowed.
  - This also allows the magnetic and electric dipole operators.
- We assume, when it matters, that the galactic halo is half particle and half anti-particle.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Scalar WIMPs

- Scalar WIMPs admit far fewer distinct interactions than fermionic WIMPS.
- Vector interactions of real WIMPs can be reexpressed in terms of scalar operators through the equation of motion.
- For complex WIMPs we again assume that the local dark matter is not asymmetric.

R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

EFT Applicability

- Now that we've constructed the appropriate effective theory we can start comparing with experimental data.
  - Note again, this particular EFT is a starting point, and different theories with other assumptions are definitely possible.
- We can only trust our theory below its cutoff scale.
  - For direct detection and indirect detection, only theories with surprisingly light exotic states will not fit into this description.
  - At colliders we expect more sensititivity to UV physics underlying the EFT, but the modifications are model-dependent.
  - The cutoff scale will always be something like the mass of the particles which mediate the interaction between WIMPs and the SM.

Confronting Experiments

- Collider Searches
  - CDF monojet study
  - LHC long-term prospects
- Direct Detection
  - Spin-independent
  - Spin-dependent
- Gamma rays
  - Fermi / GLAST line search
- Relic density, for comparison purposes.



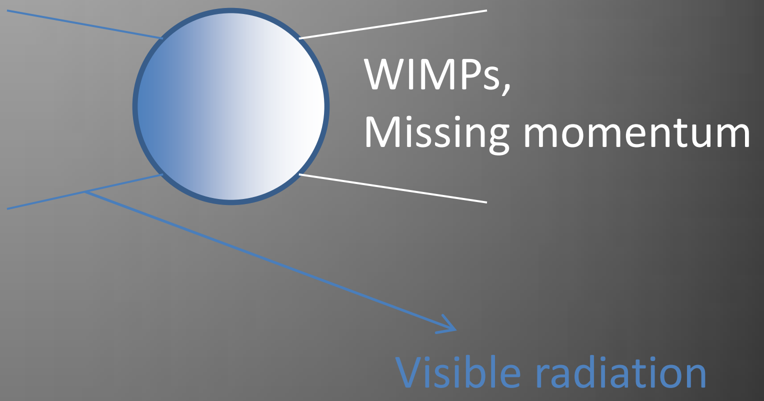


Collider Studies: Model Dependence

- The primary reason we don't have a collider line on the standard direct detection plot is that you need to make additional assumptions to make the search onto that plane.
- The standard way to search for WIMPs at colliders is to produce something else in the theory which decays down to WIMPs and SM particles.
- This process is intrinsically model-dependent.
  - Without knowing the details of the directly produced particles we can't even predict the signature to look for, let alone the correlation with direct detection.

Jets and Missing Energy

- We look at a more generic signature, where the WIMPs are produced from incoming particles and recoil against a jet.
- We compare with a CDF monojet search for ADD KK graviton production, which required:
  - Leading jet PT > 80 GeV
  - Missing ET > 80 GeV
  - 2nd jet allowed with PT < 30 GeV
  - Veto more jets with PT > 20 GeV
  - Veto isolated leptons with PT >10 GeV

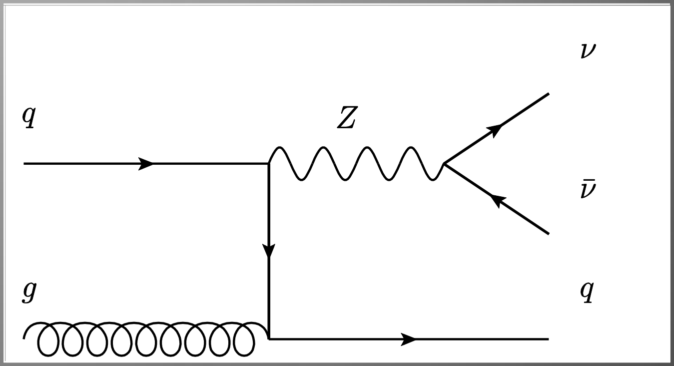


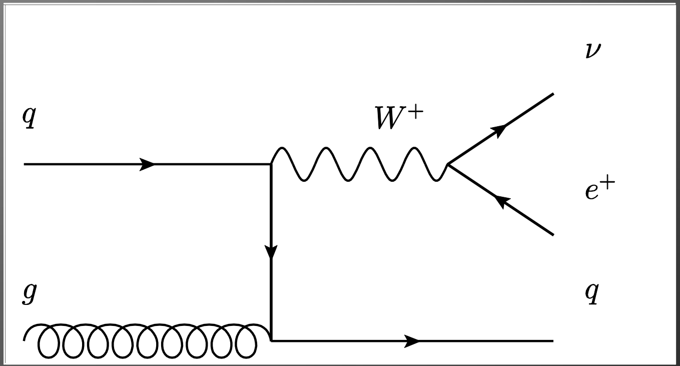
Based on 1 fb-1, CDF constrains new physics (after cuts) σ < 0.66 pb.

CDF, 0807.3132
http://www-cdf.fnal.gov/physics/exotica/r2a/20070322.mono_jet/public/ykk.html

Backgrounds

- To calibrate our simulations, we reproduced the CDF background using MadEvent with PYTHIA and PGS.
- The dominant backgrounds are:
  - Z + jets
  - W + jets, losing a lepton
  - QCD, with jet mismeasurement
    - This is subdominant, as determined by CDF, and we don't try to simulate it.





Comparison with CDF Study

- After confirming backgrounds and efficiencies against the CDF study, we find the maximum interaction strength for each operator consistent with the bound on new contributions to jets + met.
- Dominant uncertainties come from PDFs, particularly in the case of mass suppressed operators where signal comes dominantly from initial state b quarks.

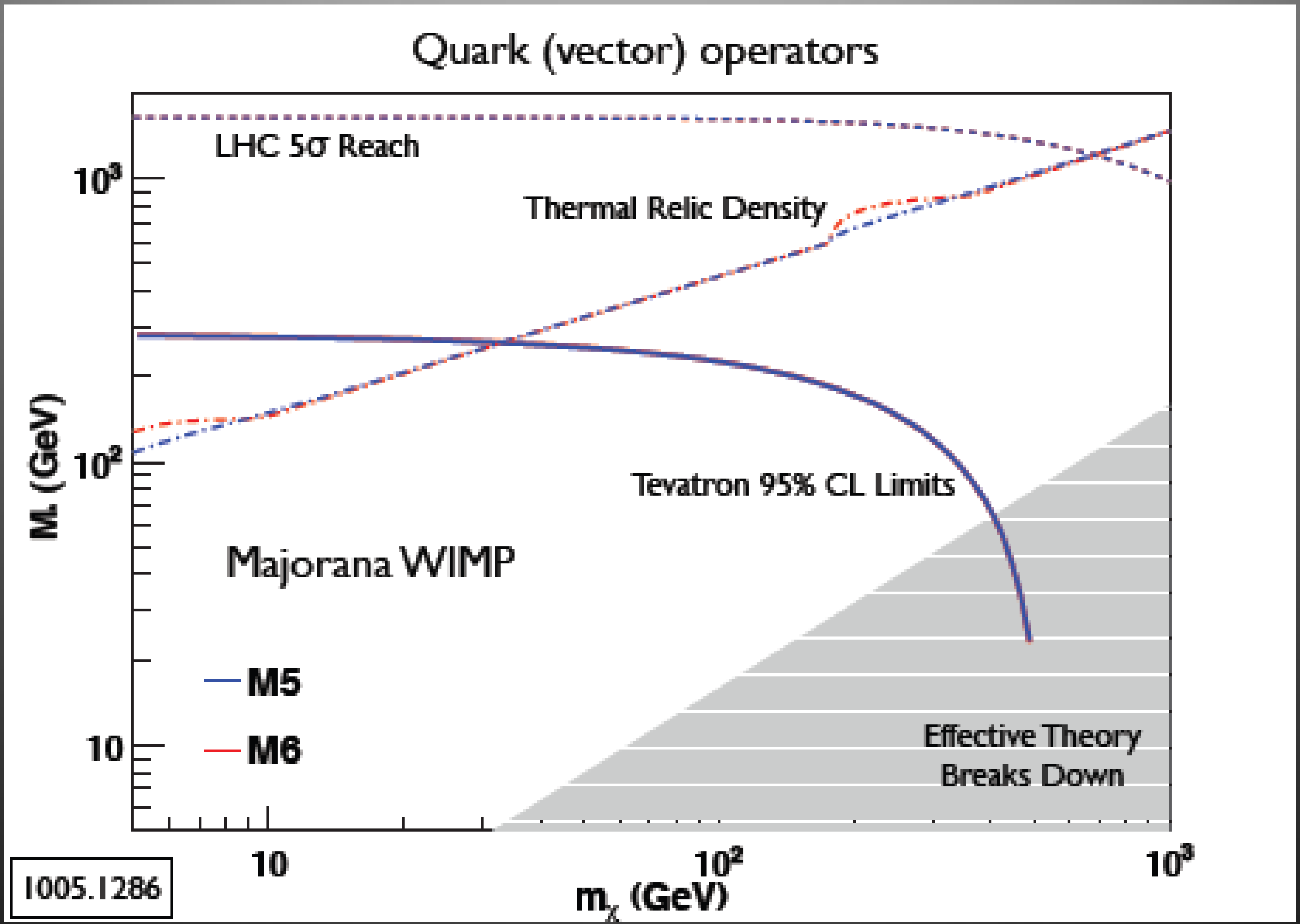
LHC discovery reach

- To estimate the LHC sensitivity we rely on the ATLAS search for jets + MET due to ADD
  - We cut at Missing ET > 500 GeV

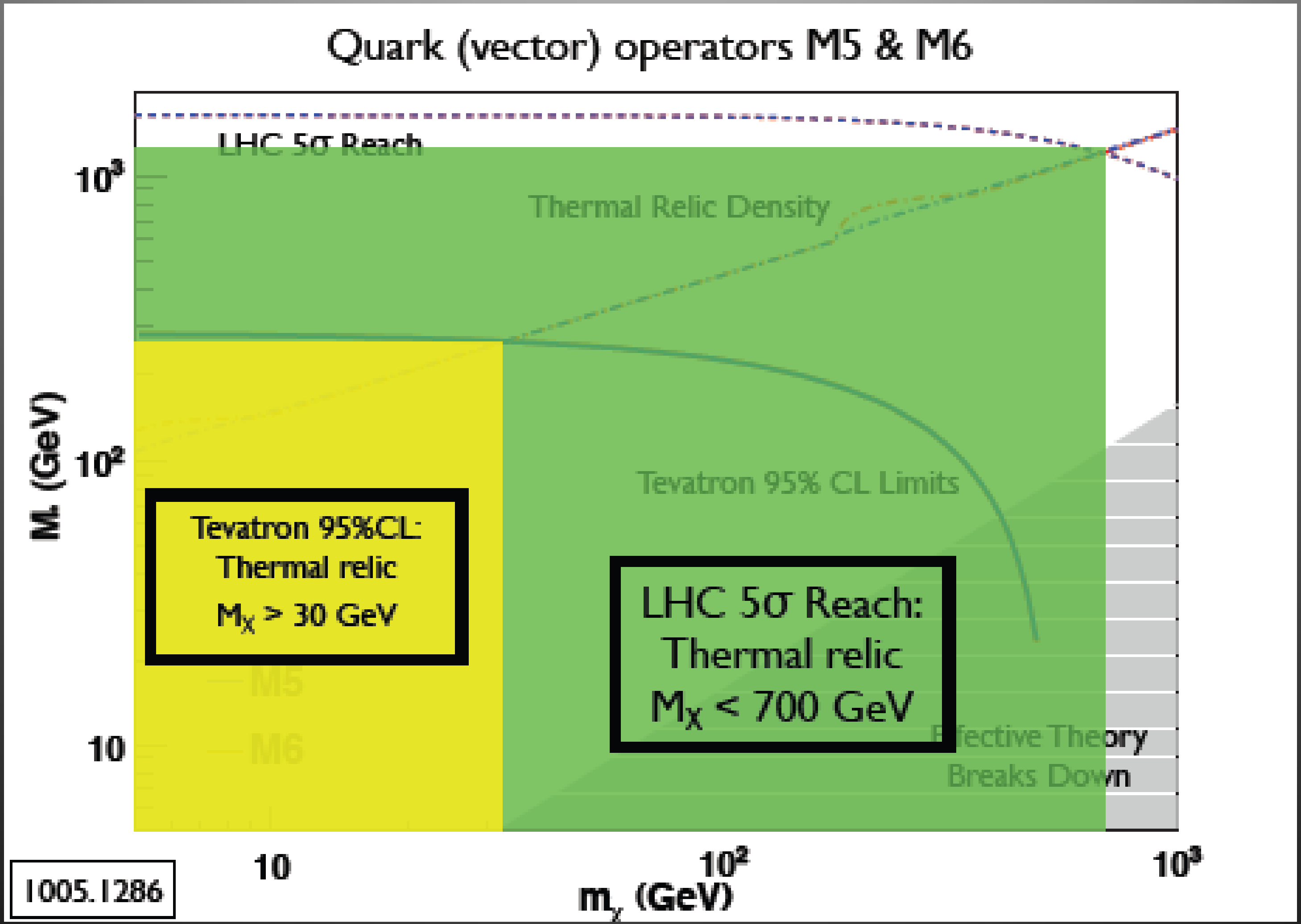
Vacavant, Hinchliffe,
J Phys G 27, 1839 (2001)

- Vetoing extra jets at such high energies is counterproductive.
- Since we’re looking in the long term, we assume 14 TeV energy and 100 / fb of data.

Example of Limits and Sensitivity



Example of Limits and Sensitivity



Axial-vector Coupling

- These operators were particularly amenable to collider searches
  - They both lead to velocity suppressed WIMP annihilation cross sections.
  - The relic density requires that they have somewhat stronger coefficients compared to other operators to overcome that suppression.
- The collider signal produces the WIMP at high velocity, therefore not much suppressed.
- We shouldn’t forget that nothing requires there to be only one operator active at the time, so that the relic density we compute assuming one operator is not robust to the inclusion of others.

Mapping to Direct Detection

- Since we have considered precisely the couplings of WIMPs to quarks and gluons, we can translate our bounds on effective operator couplings into bounds on the direct detection plane.
- There are two distinct classes of direct detection searches to compare with:
  - Spin-independent (SI) scattering looks for direct scattering of the WIMP from the nucleons in the nucleus.
  - Spin-dependent (SD) scattering looks for interactions coupling the WIMP's spin to that of the nucleus.
- We're more used to looking at the SI plane, because various predictions tell us that we'll see WIMPs there first due to the enhancement gained by scattering off of nucleon number rather than nucleon spin, which largely cancels in a nucleus.

Direct Detection

- Only certain operators contribute to WIMP scattering with a nucleus at zero velocity.
  - Three operators contribute to SI scattering.
  - Two operators contribute to SD scattering.
- We follow the usual procedure and quote WIMP-nucleon cross sections.
- Many operators have very weak direct detection bounds due to velocity suppression of the scattering.

Spin-independent:

$$\sum_q m_q \bar{q} q$$

$$\sum_q \bar{q} \gamma^\mu q$$

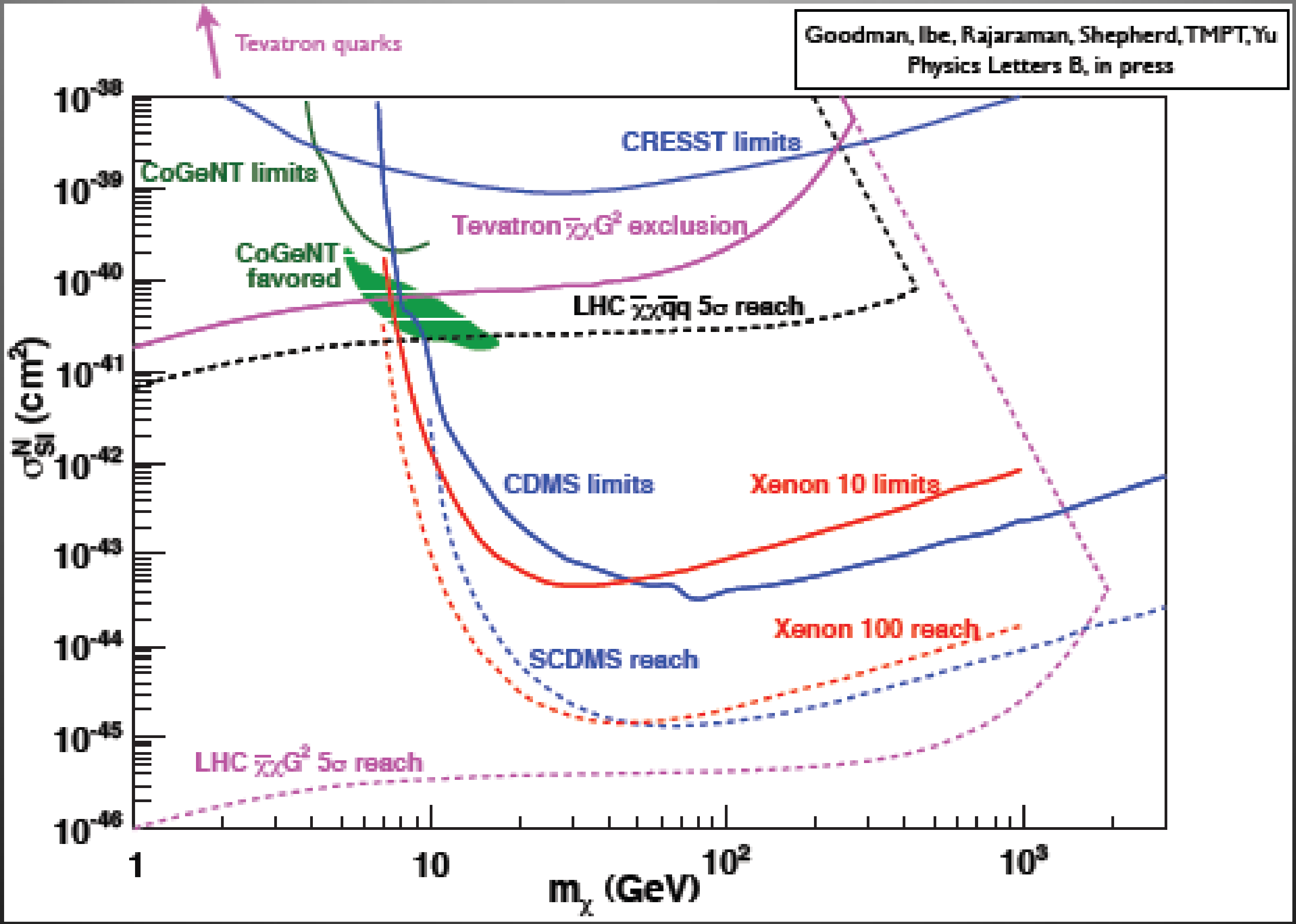
$$\alpha_s G^{a\,\mu\nu} G^a_{\mu\nu}$$

Spin-dependent:

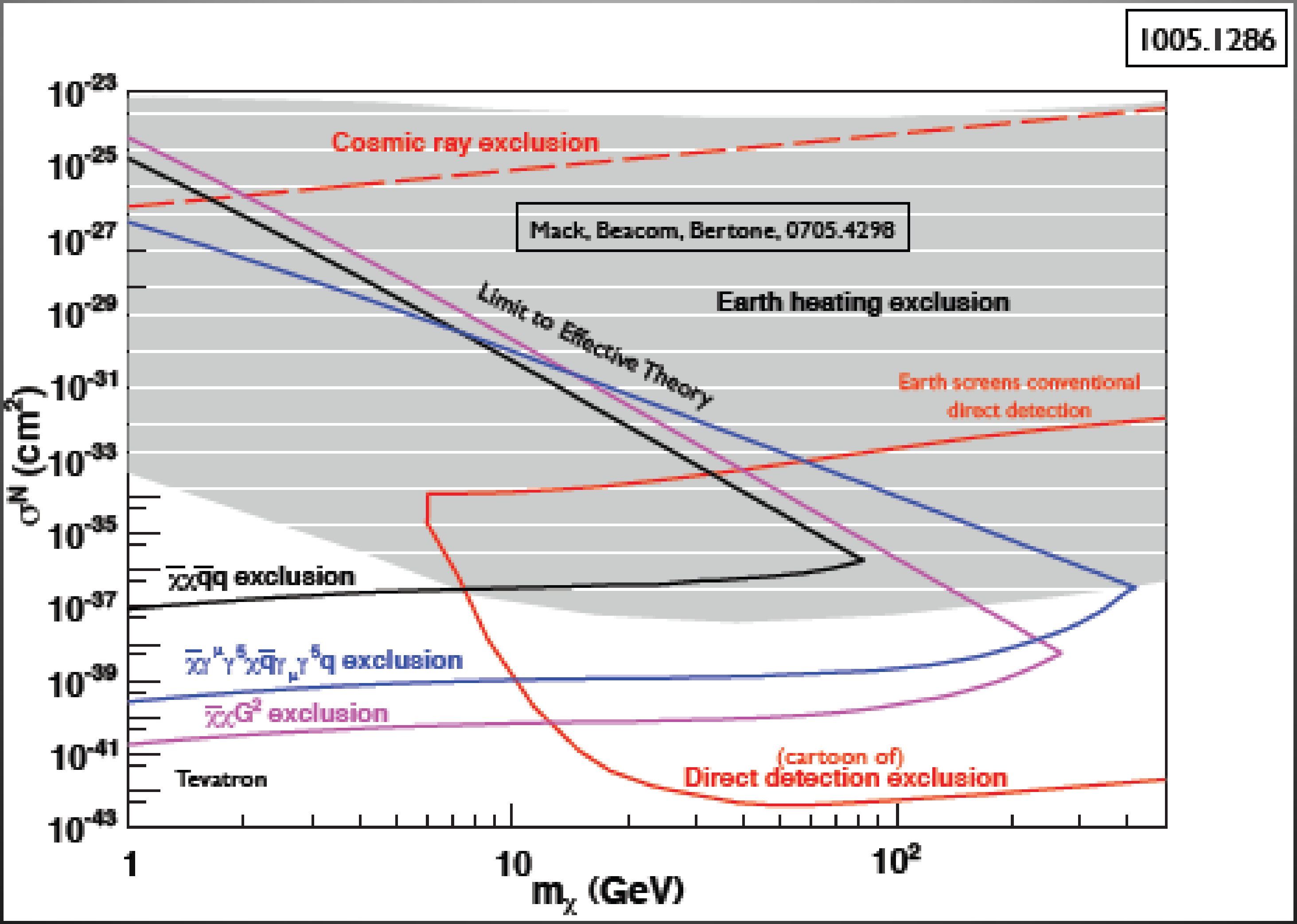
$$\sum_q \bar{q} \gamma^\mu \gamma_5 q$$

$$\sum_q \bar{q} \sigma^{\mu\nu} q$$

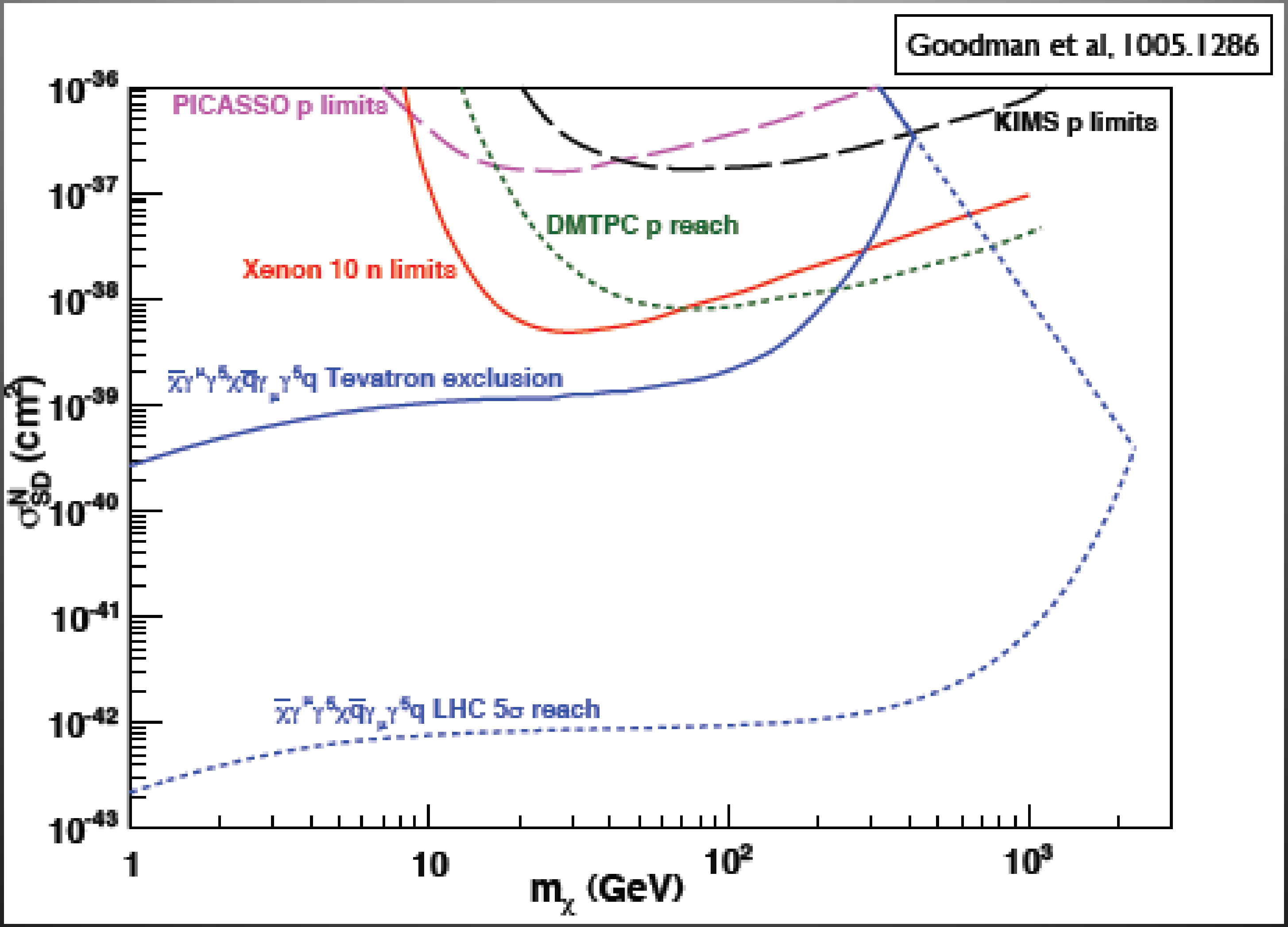
Spin-Independent



Leading Bounds on Strong Interactions



Spin-Dependent

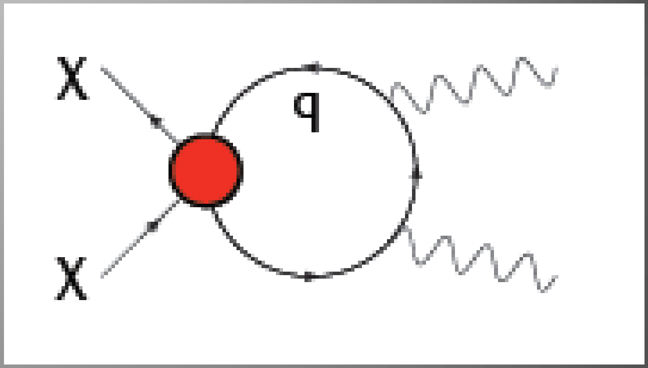


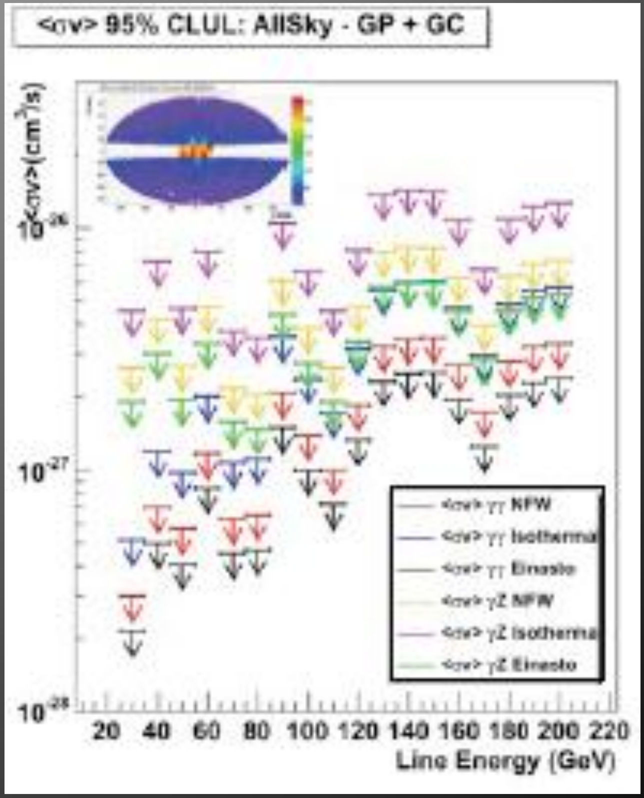
Indirect Detection

- Like direct searches, indirect searches for dark matter have the advantage that they are looking for the actual dark matter present in the galactic halo.
  - Collider missing energy could be due to other new physics than just dark matter.
- Unlike collider searches, they suffer from complicated and irreducible astrophysical backgrounds.
  - As a particle theorist, understanding these backgrounds is above my pay grade.
- I'll focus on one signal that doesn't have any known background mechanism.

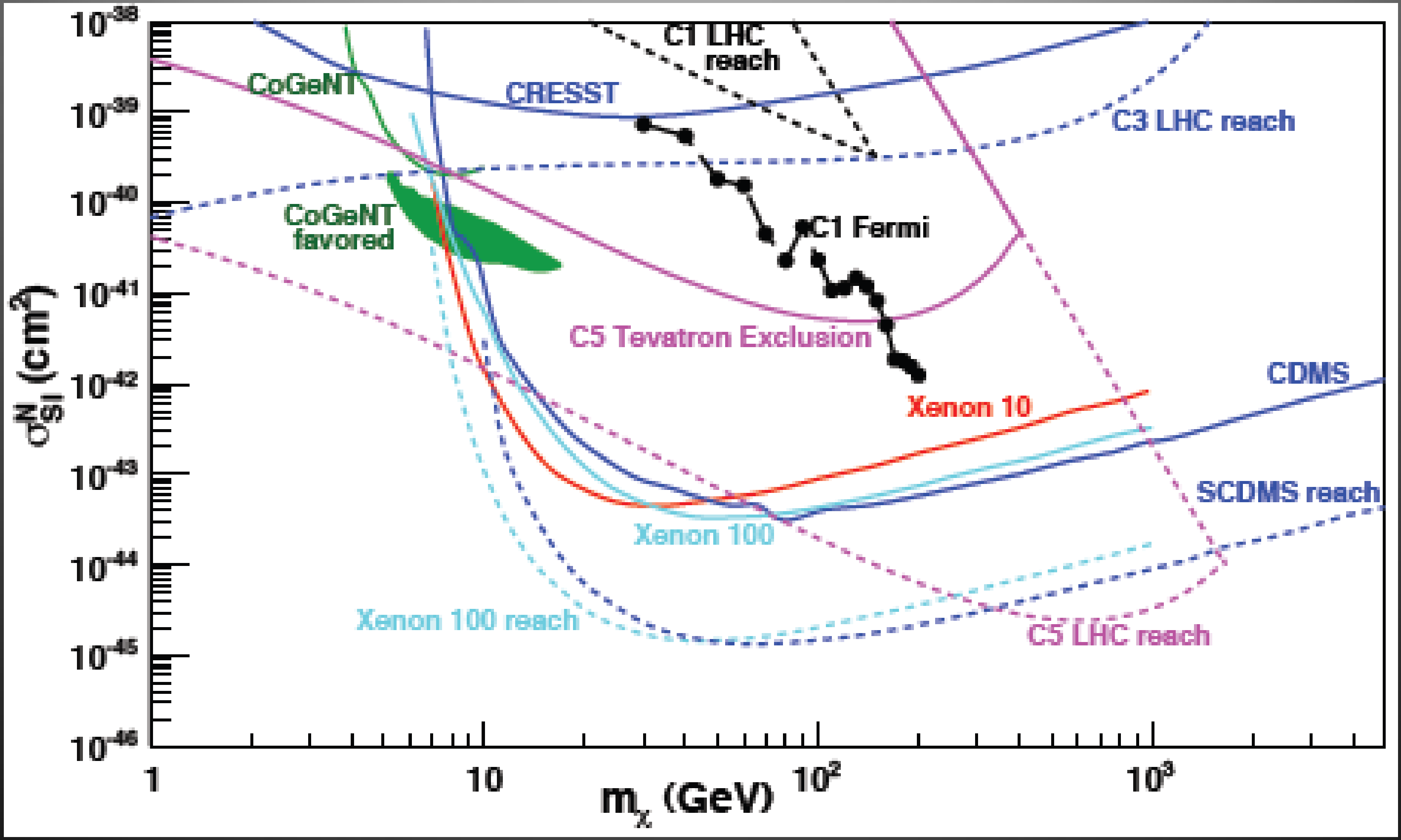
Gamma Ray Lines

- A new spectral line would be a smoking gun signature of dark matter annihilation.
- Our effective operators can lead to such a signal at one loop.
- We use the most conservative bounds quoted by Fermi/GLAST:
  - Dark matter halo in an isothermal profile.
  - These bounds are about 3x those for an NFW profile.





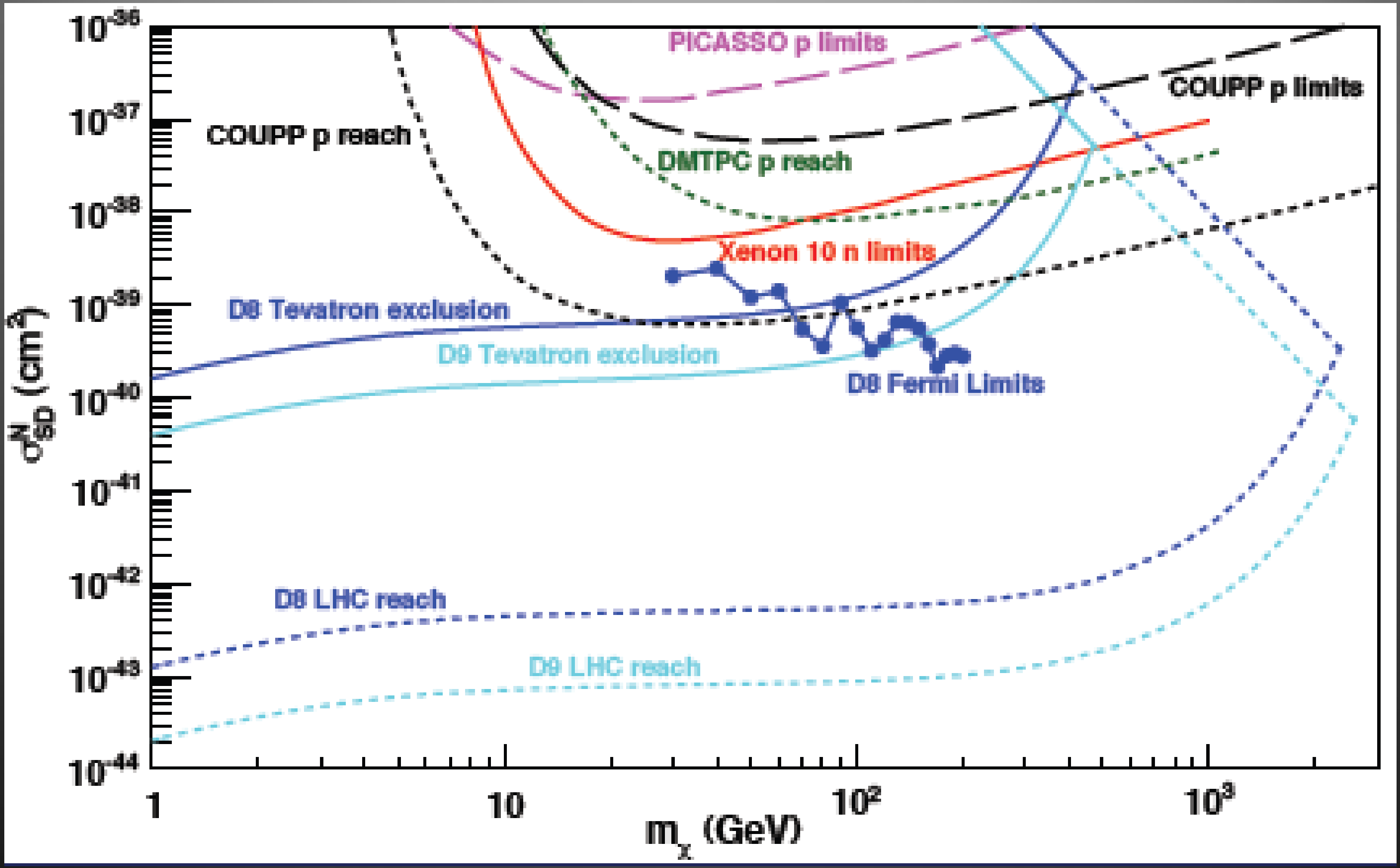
Complex Scalar WIMP, SI



SI Scattering for Scalar WIMPs

- The line search constraints on quark mass suppressed couplings of scalars are stronger than colliders, and complement direct detection nicely.
- This is not true for fermionic WIMPs, where annihilations are velocity suppressed.

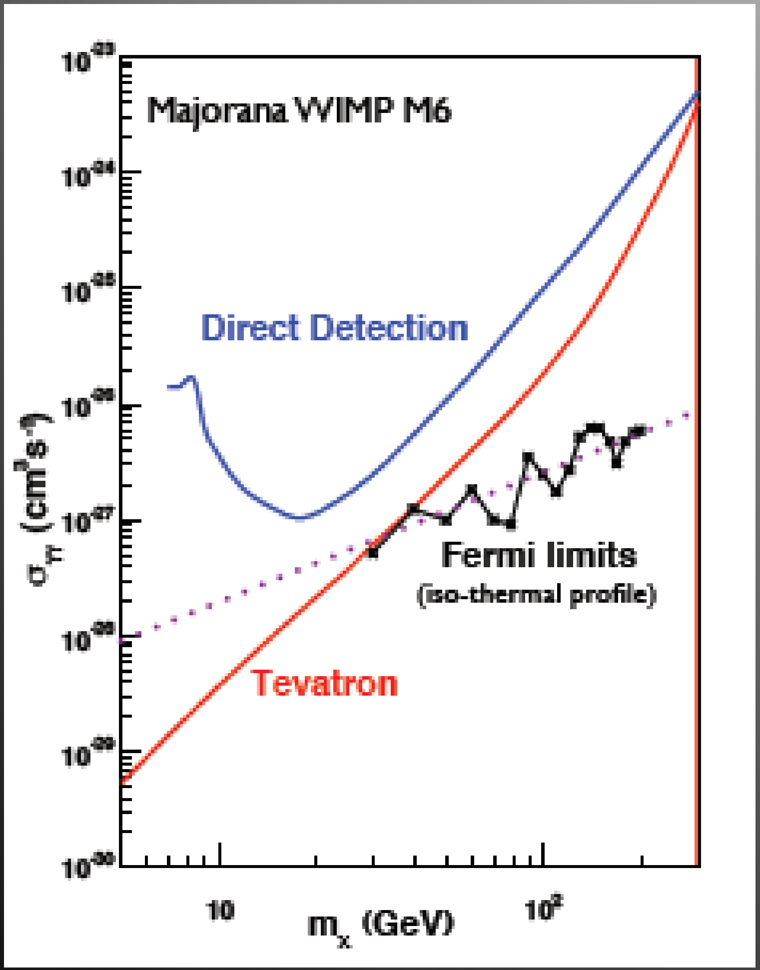
Dirac WIMP, SD



Spin-Dependent Scattering

- Colliders already do an excellent job for spin-dependent scattering.
  - Tevatron limits are better than existing and near future direct limits, except at large masses.
  - LHC limits are better by multiple decades.
- The line search is competitive with the Tevatron for moderate masses.

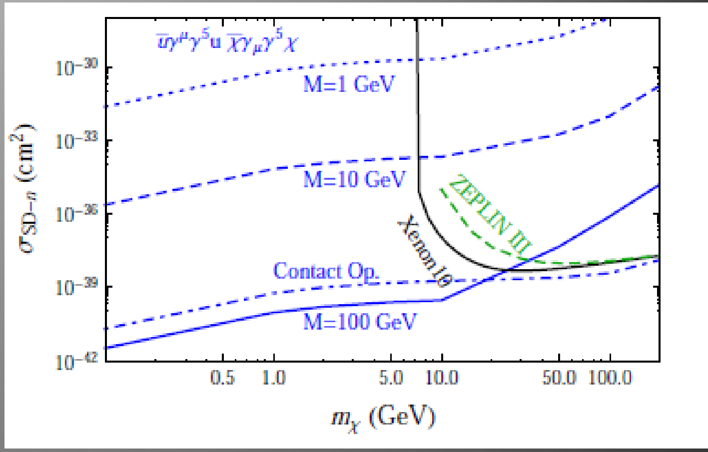
Line Cross Section



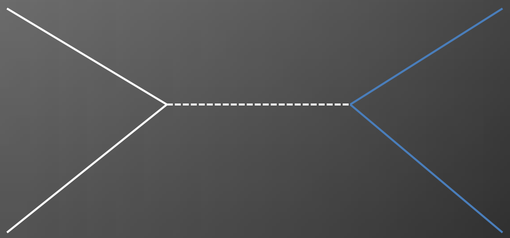
- We can also map parameter space onto other planes, for example here we have the gamma ray line annihilation cross section.

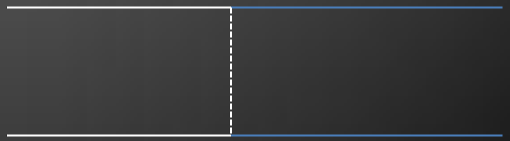
UV Concerns

- The effective theory breaks down when the mediating particle is light compared to the kinematic scales of the interaction.
  - Direct detection is largely safe from these effects.
  - Colliders can easily probe other massive new physics.
- Light mediators can significantly alter the conclusions, while SUSY-like UV completions are often subject to more stringent constraints.



Bai, Fox, Harnik [1005.3797]

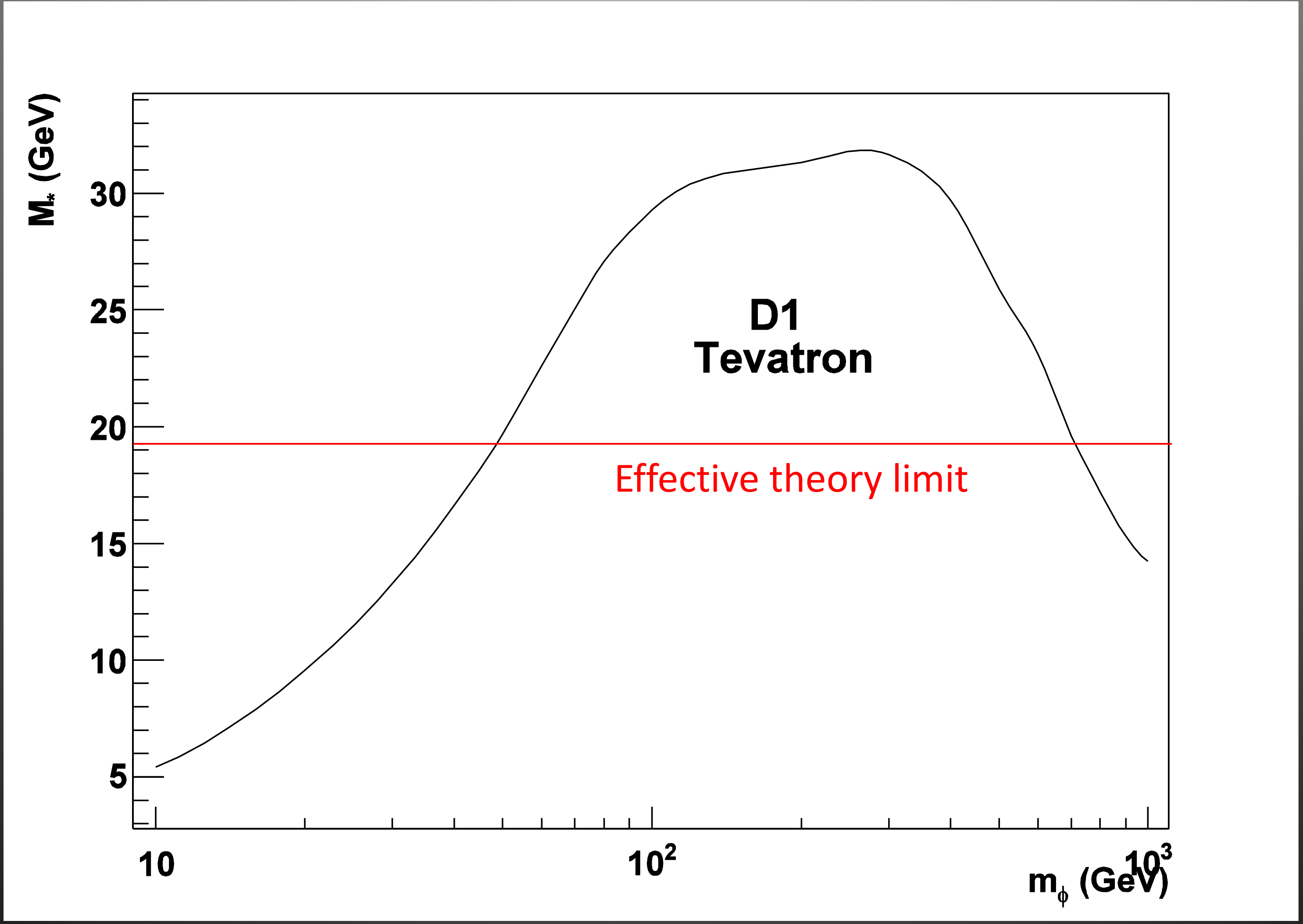




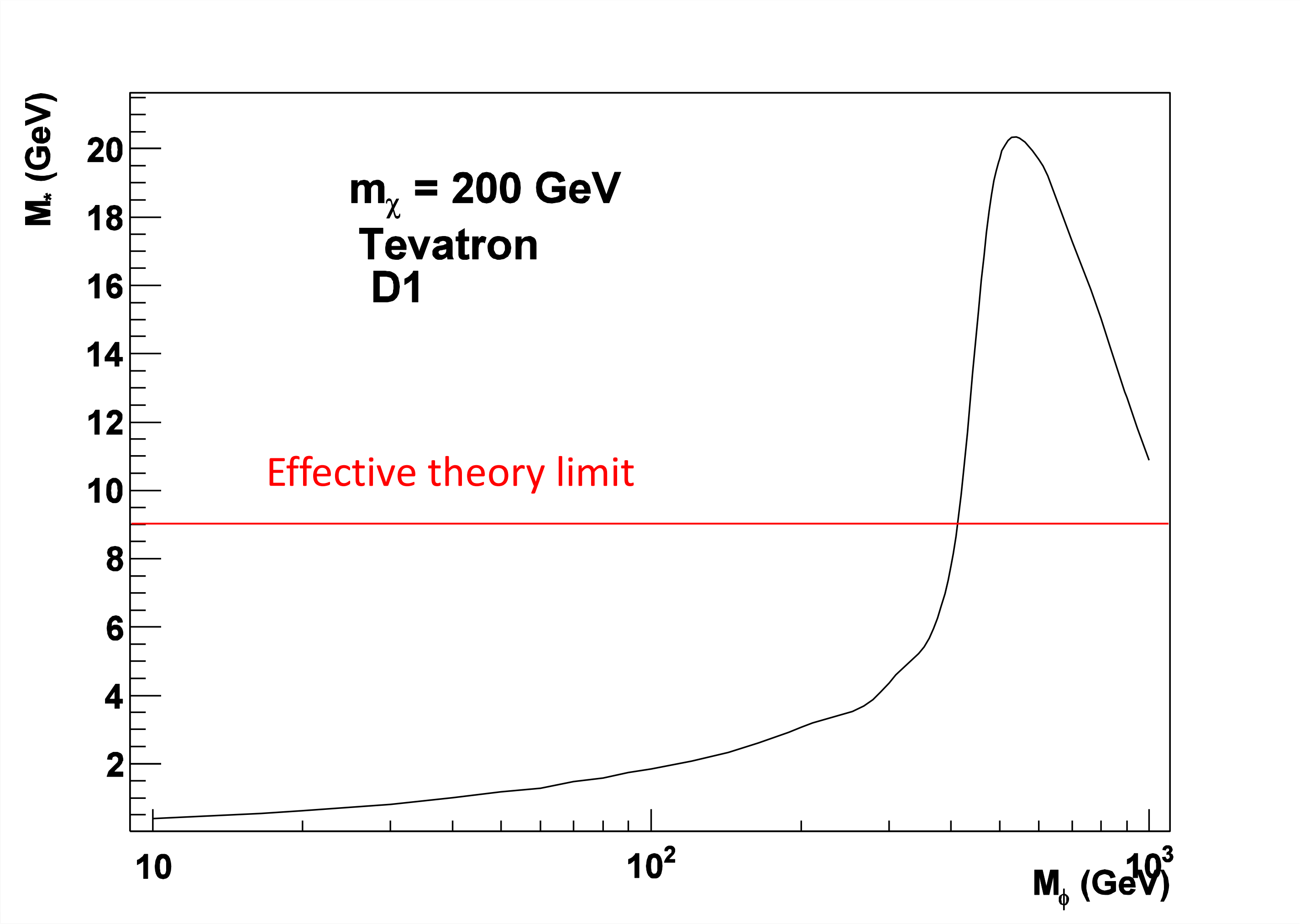
Light Mediators

- In an effort to fully understand the effects of introducing a light mediator into the theory, we write down all of the possible tree level UV completions of a contact operator like those we have discussed.
- Searching in the parameter space of coupling, dark matter mass, and mediator mass using the same CDF search, we are able to place limits on the new models.

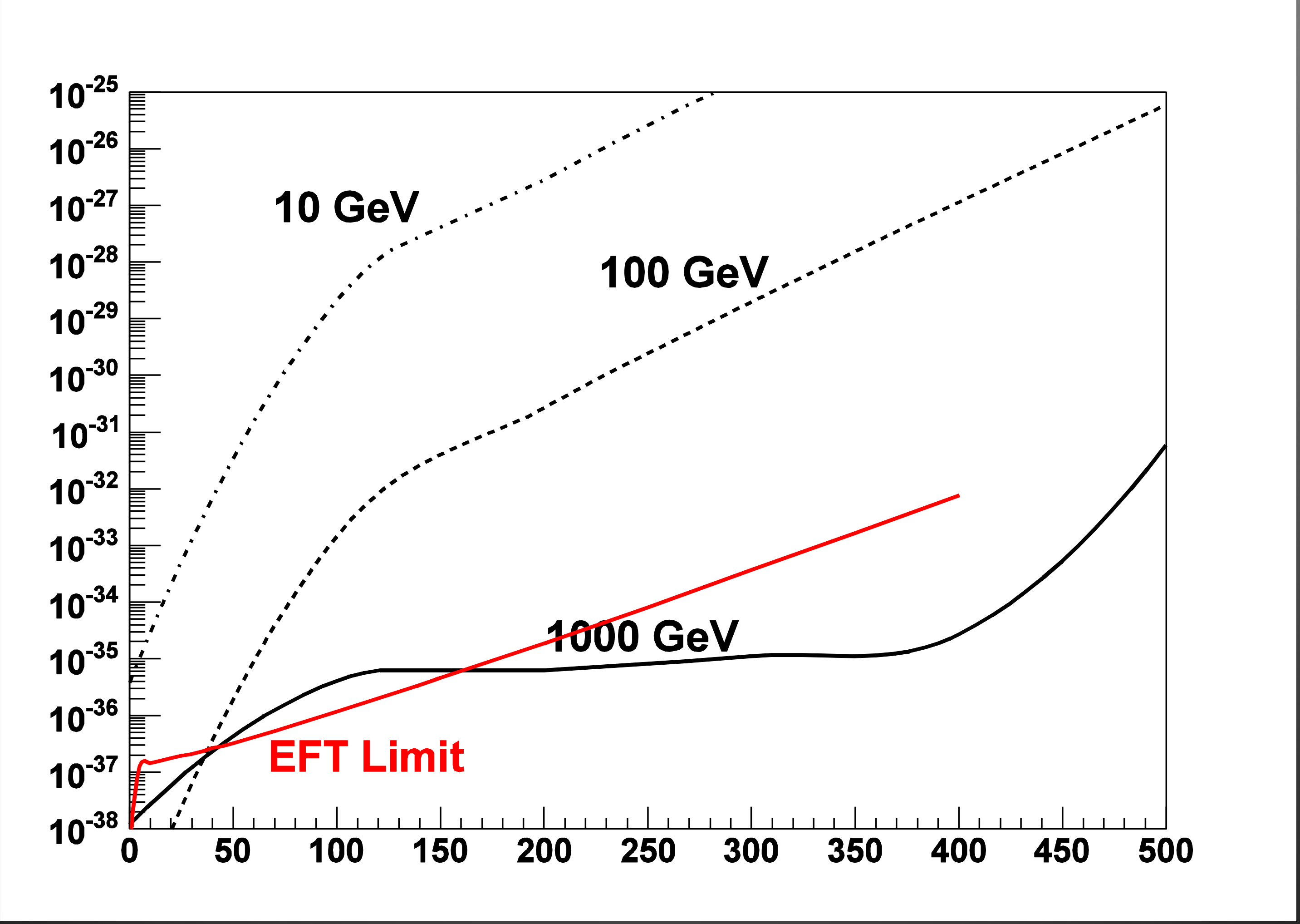
UV Complete Limits – Dark Higgs



UV Complete Limits – Dark Higgs



UV Complete Direct Detection



Outlook

- Effective field theories provide a useful language for studying WIMP interactions and interfacing the various techniques used to search for WIMPs.
- Colliders provide interesting bounds on WIMPs. We have considered the case where WIMPs are pair produced directly rather than as decay products of other new fields.
- Tevatron already provides interesting constraints on spin-dependent interactions, stronger than current direct searches.
- Collider searches are largely complementary with direct and indirect searches for dark matter.

Outlook

- These types of analyses are ripe for extension:
  - One could include the possibilities of SU(2) charged WIMPs, higgs interactions, leptonic couplings (Explored by Fox, Harnik, Kopp, and Tsai) or anything else one can think of.
- We can learn which generic types of interactions to expect in our complete theory by comparing a future detection of dark matter with the predictions of the EFT.

Bonus Material: Dirac SI